ment of the future which may have considerable impact in the field of eclipsing and intrinsic variables and that is the entry of intelligent and enthusiastic amateur astronomers into the field of photoelectric astronomy.

Amateur Astronomers

For centuries, amateurs have made worth-while contributions to astronomy. Among them have been a few great names such as Herschel, Goodricke, and Lord Rosse and, in addition, a host of other individuals who have spent their free time in making and reporting observations. Today amateurs are organized in groups large and small, and a great many cities have their astronomical units. On the national scale the organizations include the American Association of Variable Star Observers (AAVSO) and the Astronomical League. Such organizations are by no means confined to this country. The Southern Hemisphere has the Royal New Zealand Astronomical Society and the Astronomical Society of Southern Africa, as well as various groups in South America. England has produced active amateur astronomers for centuries and has, like almost every country in Western Europe, organized associations of amateur astronomers.

Further, the contribution of amateurs to the field of variable stars has been particularly great. Some organizations, such as the AAVSO, the New Zealand Society, and the amateurs in Berlin, issue their own publications. In other cases (R. Weber in France and G. Romano in Italy are examples), amateurs publish their discoveries in professional journals. To date, the bulk of such work has been done almost entirely by visual and photographic means. But there is no reason why amateurs cannot now build simple photoelectric photometers and use these with telescopes of moderate size to observe the brighter variable stars. Indeed, the *Publications of the Astronomical Society of the Pacific* have carried light curves of variables observed by an amateur, J. J. Ruiz, with equipment built by himself, and a handful of other amateurs are engaged in taking similar measures. If any appreciable number of amateurs become thus engaged, they can by sheer force of numbers do what all the professional astronomers in the world cannot do—keep under reasonably constant surveillance a considerable number of the more interesting of the brighter variable stars.

Conclusion

In closing I should probably try to predict what studies made with instruments that take advantage of the photoelectric effect may be expected to accomplish in the future, but the potential advances in instrumentation are so wide that it is not possible to predict with any confidence what the most useful applications will be, and a list of possibilities would be unduly long. Perhaps the most obvious field is the development of image intensifiers. Experimental work, which began with Lallemand at Paris and has now spread to several observatories, shows that image intensifiers are indeed practical and that, by greatly increasing the quantum efficiency of the receiver, they can indeed for many (but not all) purposes make large telescopes out of small ones—that is, permit telescopes of very modest aperture to do work which was previously possible only with the larger ones. Scanning devices, such as those developed by McGee at London, may also play their part. Whatever the details, it is certain that much of the future of observational astronomy will be written by astronomers making use of equipment which takes advantage of the photoelectric effect.

Integration of Circuit Functions into Solids

The trend in electronic circuit construction is toward microminiaturization and molecular electronics.

S. W. Herwald and S. J. Angello

The development of electronics has, since the beginning, featured progress in reducing the size and weight of equipment required to perform a given function. Substantial progress was made during World War II with the introduction of miniature and subminiature tubes. Unfortunately, mere reduction in size often leads to problems in component handling and assembly which result in increased costs and in less reliability than is found with the larger circuit function. The problem of reliability has become of such importance that recent developments have put this item ahead of size reduction in the list of objectives.

In this article we discuss the techniques which have been developed over the last decade to accomplish reduction in size and, at the same time, increase reliability, with a future potential for cost reduction. Emphasis is placed on circuit functions in solids, for this technique is in the earliest stage of research and development and shows great potential for the future.

Why Make Circuits Smaller?

One straightforward answer to the question "Why make circuits smaller?" may be found in Fig. 1. The complexity of systems is becoming very great. Pre-1940 electronic techniques will not satisfy the space requirements of the B-58 airplane. Even in ships, where one might imagine there would be no limitation on space, the problem of the size of electronic equipment is receiving attention. Space and weight restric-

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tions for equipment in missiles and satellites are other obvious reasons for making circuits smaller.

Some more subtle advantages of miniaturization may be cited. For example, in a digital computer of high speed, the time required to propagate a signal through the system can become a limiting factor. It is then necessary to compress circuits and interconnections. The lighter weight which accompanies decreased size tends to enhance the ability of equipment to withstand mechanical shock. With respect to environmental requirements, miniaturization makes hermetic sealing of complete circuits economically possible. Another advantage of hermetically sealed modules, besides protection from the atmosphere, stems from the fact that an enormous number of different circuit functions can be provided inside these modules. The module itself can be subjected to an extensive series of reliability tests—a time-consuming and expensive process. Once carried out, this procedure need not to be repeated in its entirety each time a new circuit is made inside the module. The economies of standardization will show up ultimately in lower costs than for conventional circuits.

One aim of the various miniaturization techniques is reduction in the number of solder-joint interconnections in a system. It is well known that solder joints are reliability hazards. The probability of survival (P) of a system during the course of a mission is the product of the probabilities for survival of the n individual components and connections making up the system: that is,

$$P = P_1 \times P_2 \times \ldots P_i \times \ldots P_n$$

An interesting deduction may be made if we establish the average survival probability of the components and connections by the expression

$$P_{av} = \sum_{i=1}^{n} P_i/n$$

for then the total survival probability for the system is

$$P = \left[\sum_{1}^{n} P_i/n \right]^n$$

In this form it may be seen that more is to be gained by reducing the value of n than by improving the individual probabilities (P_i).

Maintenance is an important problem in the application of electronic systems. Smaller, encapsulated circuits will help in at least two ways. Greater reliability will reduce maintenance, and the compact modules will simplify replacement. As circuit modules become more economical, more complex circuits may be included in the replacement module. This will transfer complex maintenance problems to the manufacturer, who has expert personnel and equipment for this purpose, and field problems may then be handled by relatively inexperienced people.

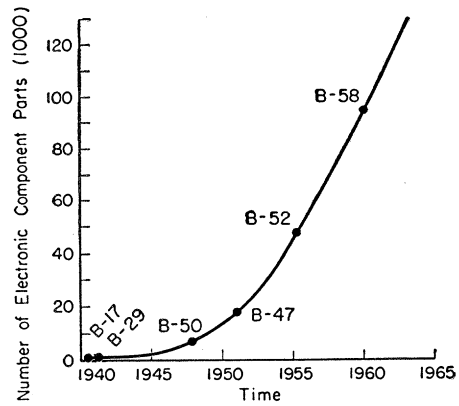


Fig. 1. Trend of complexity of electronics in U.S. Air Force weapon systems.

How To Make Circuits Smaller: The Transistor

It has been pointed out many times in the literature that the thermionic vacuum tube is a very inefficient device for information-handling functions. Whereas microwatts to milliwatts of power are usually sufficient for communication, the filaments of vacuum tubes require tenths of watts solely for the purpose of boiling electrons from the cathode surface. The requirement for such sources of heat within electronic equipment seriously limits the number of parts which can be contained in a unit of volume while still maintaining a safe operating temperature.

In July 1948 the invention of the transistor was announced (*1*). This device has power requirements which are comparable to the signal levels that are being handled. The transistor does not eliminate the problem of power dissipation in electronic circuits, but it does permit an increase in parts density of several orders of magnitude before the temperature rise becomes serious.

Two important developments that followed quickly upon the announcement of the transistor were the *p-n* and *p-n-p* (*2*) junction devices. These developments are the present basis for the integration of circuits into semiconductor substrates. Since the equivalent circuit of a *p-n* junction biased in the high-resistance direction is a capacitor shunted by a high resistance, a three-layer *pnp* (or *npn*) semiconductor substrate provides the essentials to form resistance-capacitance active networks.

Major Approaches to Small Circuits

There are three important approaches to the construction of small circuits. These are: (i) microcomponent assembly; (ii) two-dimensional microminiaturization; and (iii) functional electronic blocks. We shall discuss the first two briefly to establish the historical perspective, then we shall concentrate our attention upon the state of the art and the future problems of the third.

Microcomponent assembly. Microcomponent assembly is exemplified by the Navy "Tinkertoy" project (*3*) and by the Signal Corps "Micromodule" program (*4*).

The first obvious advantage of this approach is the availability of an almost complete range of components from which to plan the construction of systems. If a proper supplier-assembler relationship is set up, cost reductions through mass production should be realized. The interconnection of circuits is combined with the assembly structure, as shown in Fig. 2. Because of light weight and small size, this structure should withstand mechanical shocks. The final structure is resin-embedded to provide environmental protection. No appreciable reduction in numbers of components and soldered joints is achieved by this approach. Danko *et al.* (*4*) give a comprehensive description of the program, with references to pertinent literature.

Other assembly schemes are being used which are similar to the micromodule. Several manufacturers of semiconductor devices are producing microminiature diodes and transistors under standards suggested by the TR 25.1.1 subcommittee on microminiature components of the Electrical Industries Association. Compatible resistors and capacitors are becoming available. Fotoceram boards can be etched with slots and holes to hold the components, and many ingenious interconnection schemes have been devised. These techniques offer solutions to the problem of constructing small equipment with minimum lead time.

An interesting variation of the concept is evidenced in the thermionic

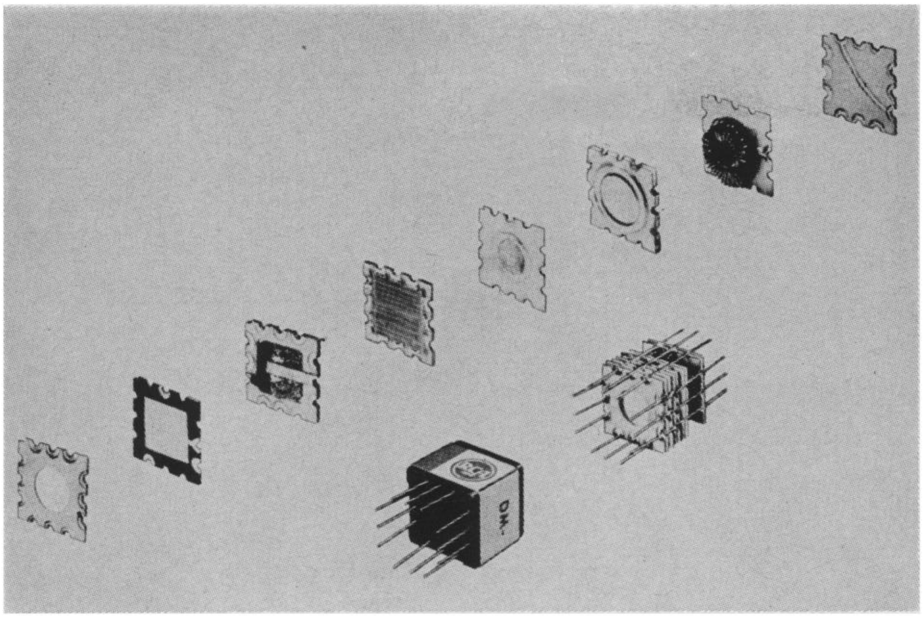


Fig. 2. Exploded view of a typical micromodule. [Radio Corporation of America]

micromodule. This approach consists of building high-temperature resistors and capacitors into the envelopes of all-ceramic thermionic tubes. Devices of this type are especially appropriate for high-temperature ($\sim$ 500°C) operation and survival in high-intensity nuclear radiation fields.

Two-dimensional microminiaturization. As the name implies, this scheme endeavors to make the thickness dimension of a circuit vanishingly small —hence, to make the circuit two-dimensional. Such two-dimensional circuits can then be closely stacked to form the three-dimensional equipment module.

All of the classes of schemes mentioned have at least one thing in common; they depend in one way or another upon the mechanical support of a thin wafer. The micromodules use 0.310- by 0.310- by 0.010-inch alumina or Fotoceram wafers, depending upon the components to be supported. Two-dimensional circuits use similar wafers, and functional blocks use silicon, germanium, or other semiconductors, which may or may not be supported by a ceramic wafer. Because of this common feature, it can be seen that, as developments proceed, a mixture of the three techniques is likely, with the mix determined at any given time by factors such as availability, economy, tested and proved reliability, and performance.

In two-dimensional microminiaturization an attempt is made to process resistors, capacitors, and interconnections on a substrate, preferably in the fewest possible manufacturing steps. Thus, metallic resistors may be made by evaporation of Nichrome on alumina substrate, and capacitors may be made by successive evaporations of metal and dielectric. A detailed description of these techniques is given in (*5*).

Some recent developments in deposition of films make this scheme attractive. A process for sputtering thin, adherent tantalum films has been described (*6*) which has several interesting consequences. The tantalum film can be anodized to form one plate and the dielectric of a capacitor. Since the tantalum oxide is very thin, a large capacitance can be obtained in a small area. Tantalum film resistors can be made which are stable both electrically and mechanically and which exhibit excellent properties of adherence to the substrate. Stable films of this type can provide the basis for circuit interconnections on the substrate which are more reliable and easier to make than soldered joints.

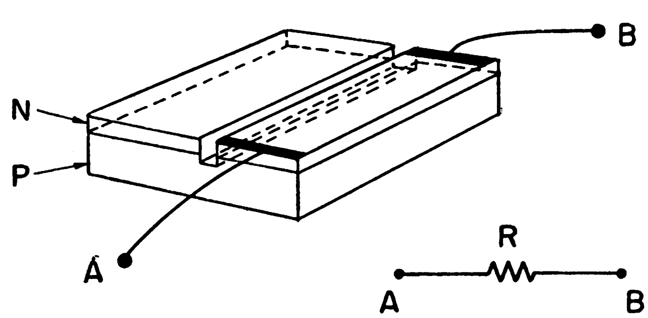
Techniques of this type, coupled with a good scheme of encapsulation (*7*), have potential for use in future systems.

Functional electronic blocks. The integration of circuit functions into solid substrates marks the most recent and advanced approach to the construction of small circuits.

The primary purpose of the functional-block scheme is to rearrange the internal physical properties of a solid to perform a circuit function more complicated than that performed by an individual component. The idea is best described by considering very simple solid structures and then proceeding to more complicated examples. Most of the work so far has centered upon semiconductors, but this is not a necessary restriction. This is a reflection of the fact that semiconductor technology is farther advanced than other pertinent solid-state-device technologies.

Simple Resistance-Capacitance Circuits

We shall illustrate the functional-block scheme by describing how resistors and capacitors can be integrated into a block of *p*-type silicon semiconductor of high resistivity ($\sim$ 200 ohm cm). Figure 3 depicts such a *p*-type block with a thin skin of *n*-type, low-resistivity silicon obtained by diffusing antimony into the block. This procedure is a common one for the manufacture of semiconductor devices. Figure 3 also shows a thin slot cut through the skin to isolate a region to which leads have been attached. The region is iso-



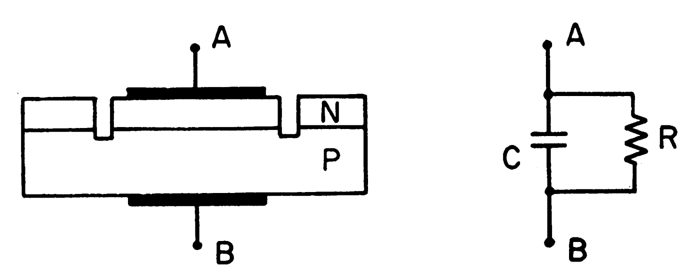
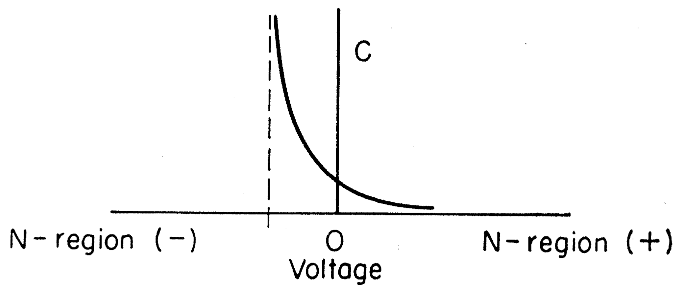


Fig. 3 (left). A silicon block with thin diffused layer. Fig. 4 (right). A diffused silicon block with metallic connections.



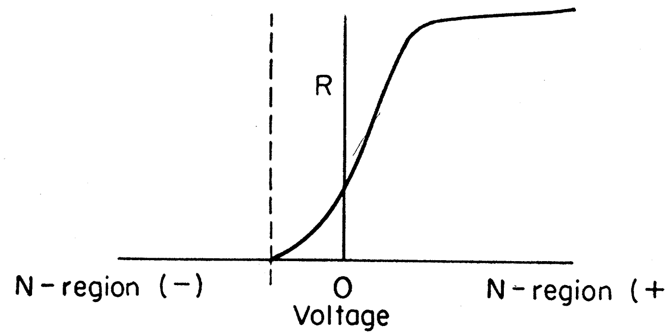
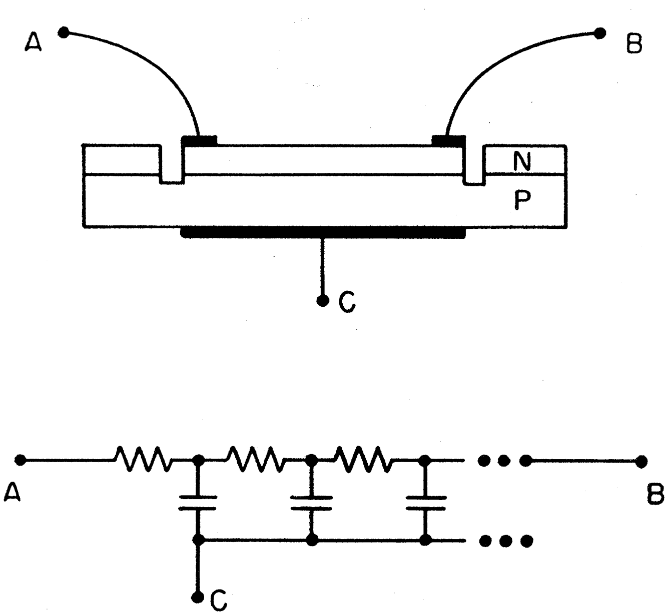


Fig. 5 (left). Capacitance versus voltage for an *n-p* junction. Fig. 6 (right). Leakage resistance versus voltage for an *n-p* junction.

lated because the substrate- to skin-resistivity ratio is greater than 10^2. The slotting operation may be carried out with a fine diamond saw, a scriber, a fine sand blast, or an etch. Etching through Photoresist masks is becoming a common technique. This is the technique developed for surface shaping in two-dimensional microminiaturization. Leads may be attached by furnace fusion, ultrasonic welding, or thermocompression bonding. Other reliable processes are being developed.

A range of resistors may be fabricated on this principle by varying the thickness (by diffusion time, temperature, and type of diffusant), the length, and the width of the *n*-type skin. The range from a few tens of ohms to approximately one megohm may be realized by this method. Ten-percent tolerance can be achieved if trial and error resistance trimming is permitted. The temperature coefficient of resistance follows that for the high-carrier-density diffused skin, which can range from slightly negative, through zero, to slightly positive. Some advantages of this configuration are derived from the intimate connection of the resistor film to the substrate. Silicon is a good heat conductor, and the thermal drop between resistor and substrate is low. Several resistors located on the same substrate will maintain nearly the same temperature as temperature varies over the operating range. Careful designs and appropriate circuits can take advantage of the common temperature to introduce internal compensations for stability. Two disadvantages are that precision resistors have not been made at this stage of development and that very low temperature coefficients have not yet been achieved.

The attachment of metallic areas on each side of the diffused junction (see Fig. 4) results in a capacitor because an *n-p* junction has the equivalent circuit shown in the figure. This capacitance is not constant but varies with applied voltage in the manner illustrated in Fig. 5. At the same time, the resistance across the capacitance varies as shown in Fig. 6. With a few volts positive on the *n*-region, the resistance attains the megohm range, so that a rather good



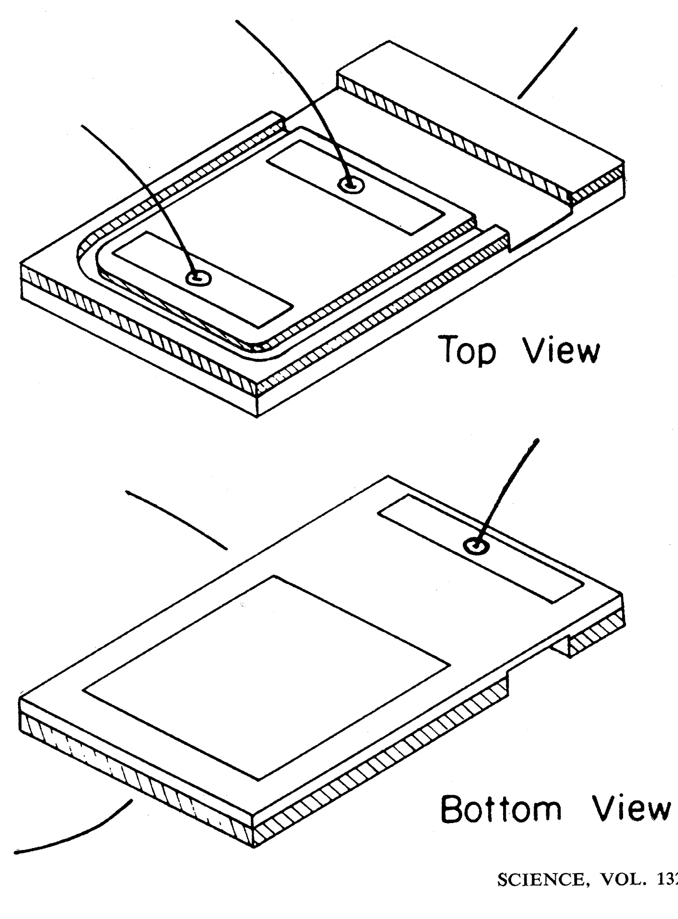
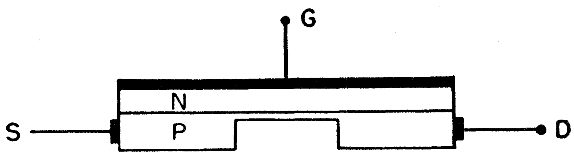


Fig. 7 (left). Phase-shifting network with distributed resistance and capacitance. Fig. 8 (right). A notch filter functional block.



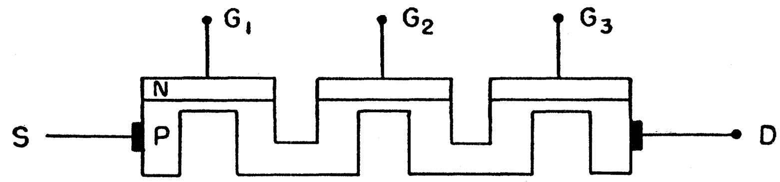


Fig. 9 (left). Basic unipolar transistor configuration. Fig. 10 (right). Example of unipolar transistor logic gate.

capacitor can be obtained under this operating condition. Capacity values are small, being of the order of 0.005 μf/cm^2. Larger values in the 1 μf/cm^2 range are more appropriately obtained by two-dimensional techniques, such as the anodized tantalum film. The variation of capacitance with voltage can be useful or a handicap depending upon the application.

An interesting extension of the capacitance block is obtained by combining the configurations of Figs. 3 and 4. Figure 7 illustrates such a configuration, which acts as a phase-shifting network and low pass filter. In this application a deviation from discrete components results because the resistances and capacitances are distributed throughout the block.

Another extension is illustrated in Fig. 8. A resistor, consisting of part of the block, is inserted in series with the metallic condenser plate of Fig. 7. The result is a function block which is frequency-selective, like a bridged-T circuit. Such a narrow frequency band is passed that the term *notch* filter (*8*) is given to this block. This functional block replaces an array of at least nine resistors and condensers, with the soldered joints replaced by internal block configurations. Consequently, only the minimum number of required leads emanate from the block.

Unipolar Transistor Blocks

Another type of functional block which may be fabricated from an *n-p* block depends upon the properties of the unipolar transistor. Figure 9 shows the basic principles. A region of the order of 10^{-4} centimeter thick around an *n-p* junction is depleted of current carriers. When $n(+) - p(-)$ bias is applied, the depletion layer widens and becomes a higher resistance. This is the high reverse resistance of an *n-p* junction diode. In Fig. 9, a cut in the *p*-layer has been made to extend close to the depletion-layer region. This cut should extend deep enough so that under reverse bias the resistance measured between *S* and *D* becomes very high. At zero bias, the *S-D* resistance is relatively low. Thus, a bias on the *n-p* junction acts as a gate to open and close the channel between *S* and *D*.

Some very complex and useful block functions can be invented on the basis of the principle of the unipolar transistor. A simple extension of Fig. 9 can result in a logic gate circuit (*9*). Figure 10 depicts a direct coupled gate. The top slots through the *n*-layer into the *p*-region form resistors between the unipolar transistors. A circuit exists between *S* and *D* if none of the gates are biased. No circuit exists if G_1 or G_2 or G_3 are biased to close the gate.

This discussion has by no means exhausted the possibilities for functional devices to be constructed in an *n-p* silicon block. We point out here (this is discussed more fully below) that progress in the development of functional electronic blocks depends strongly upon the invention of new configurations and construction techniques.

It is clear that one may proceed to develop more complicated functions by adding additional layers to the silicon block. We have seen how two layers provide resistors, capacitors, *n-p* diodes, unipolar transistors, and combinations thereof. Three layers introduce many variations, according to the construction technique. Of course, all of the functions possible with two layers are also possible with three. Adding a fourth layer introduces four-layer switching diodes, trinistors, trigistors, and other varieties of switches with or without control electrodes.

To complete the discussion, we describe below a block involving transistors and one involving switches.

Transistor Block

A basic circuit which may be designed to serve either as a low-level audio, a high-level audio, or a video amplifier is the Darlington connection shown in Fig. 11. The function block shown below the circuit can be constructed as follows. The common collector connections are provided by the metal electrode located on the *p*-region. The input base connection is a metal which forms an *n*-connection with the *n*-region. A *p*-alloy junction to the *n*-region completes the first *pnp* transistor. The second transistor is constructed similarly. Interconnection is effected by allowing the *p*-emitter of the first transistor to fuse at one point to the *n*-base of the second transistor. This illustration is oversimplified in that temperature-compensation resistors and coupling capacitors are omitted. These elements may be included, to result in more stable operation with respect to temperature variations.

A more complicated transistor function block is the bistable multivibrator (*10*) or "flip-flop" block. This type of device contains at least two capacitors, four resistors, and two transistors.

Four-Layer Switch Block

In the discussion so far, the types of function blocks described have had a close analogy with the circuit being replaced. Only a slight deviation from this was noted in the case of distributed resistance-capacitance blocks. It is possible to construct blocks which perform a function having no resemblance to the circuit being replaced. Figure 12 shows a four-layer diode in series with a resistor. Under the sketch is a volt-ampere characteristic. If the load resistance is that shown by the dotted line, the switch will have two stable states, one at high resistance and one at low resistance. A higher load resistance, such as *R*, will permit no stable state, and the circuit will oscillate with a saw-tooth output wave form. Because the load line may be shifted on the characteristic by varying the applied voltage, the relaxation time or output frequency is a function of voltage. This behavior has led to the suggestion that this type of block may be used as an analog-to-digital converter (*11*).

Figure 13 shows several function blocks developed by Westinghouse Electric Corporation for the Air Force.

Future of the Functional Electronic Block Concept

The original studies of function blocks were aimed primarily at reducing the number of interconnections to provide electronic circuits of high reliability and stability against shock. The nature of the concept, however, has led directly to the miniaturization of circuits discussed in this article. Future progress in functional blocks is linked to progress in at least three areas. These are: (i) invention of block configurations; (ii) development of processing techniques for solid-state devices; and (iii) development of new materials.

Invention, Techniques, and Materials

It has been pointed out above that invention is important for progress in functional blocks. To construct analog blocks which follow circuit configurations is possible and useful; however, the aim of simplification will not be furthered in this manner. Not only are new types of block configurations needed but enhanced usefulness of blocks already known is also desirable. Interactions among components on a block can be troublesome, but ingenuity can turn some of these interactions to advantage.

Perhaps one of the most serious limitations of miniaturization is the problem of heat dissipation. Designs of blocks to perform a given function with lower power dissipation is one approach. Better schemes to remove heat is another. Many facets of design enter into the dissipation problem—the tolerance of resistors, for example. The looser the tolerance prescribed in a given circuit, the higher the power dissipation that one can expect. The ideal is to design circuits which may tolerate reasonable spreads in component characteristics and at the same time operate at low power.

More investigation of circuits in the general area of resistance-capacitance active networks is needed if the full potential for two-dimensional miniaturization is to be realized. Circuits containing inductances are usually large and they must be eliminated insofar as possible.

We also need to construct functional blocks with other than semiconductor substrates. Magnetic films, titanate substrates, ferroelectric materials, electroluminescent cells, and Hall generators are fruitful possibilities for the construction of function blocks.

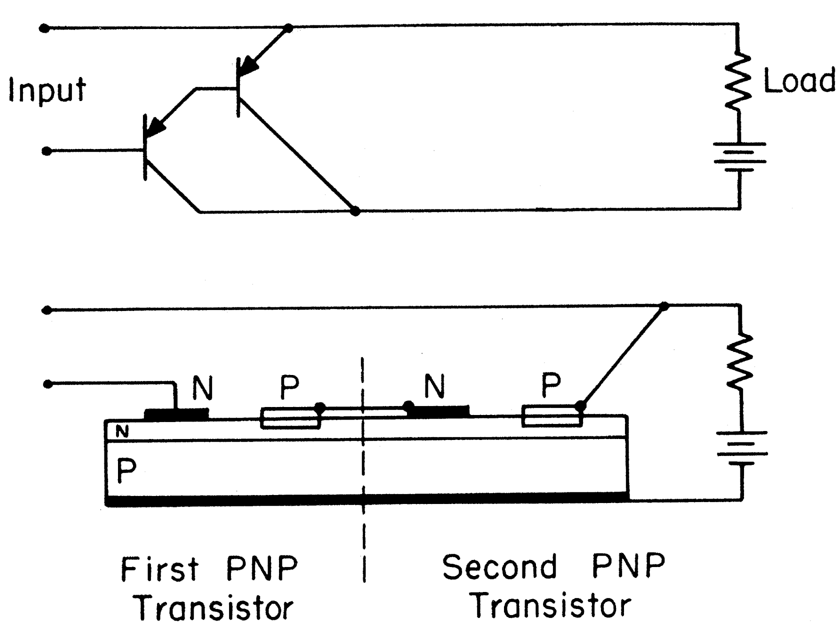
Solid-state devices are also contributing to microwave technique through the various masers, parametric amplifiers, and distributed-line devices. More may be expected in this area.

Construction of a function block, once it has been designed, depends of course upon our ability to fabricate the junctions, slots, holes, and so on needed to perform the function. Another important consideration is that one should aim not to make just one good block but to make a number with acceptable economical yield. This subject is discussed in more detail in (*9*).

More development work is needed in the techniques of masking, etching, electron-beam cutting, and other block-shaping techniques. In this area, two-dimensional microminiaturization and fabrication of function blocks have much in common. One scheme can supplement the other. More development is needed in thin film deposition of capacitors. Refinement of circuit and block interconnections to give reliable and economical use of these techniques will speed their adoption by the electronics industry.

The importance of construction techniques is emphasized by the invention of a four-layer device which is a transistor with two hook collectors (*12*). This device can be operated as a full adder and would be a significant computer function block if it could be constructed with consistent reproducibility. At the present state of the art, the required tolerances cannot be maintained consistently with economical yield. Other instances of need for precise process control will undoubtedly arise as the field develops.

The materials problem has at least two major aspects: (i) New semiconductor materials with new properties are needed to make new functions possible; (ii) improved techniques for



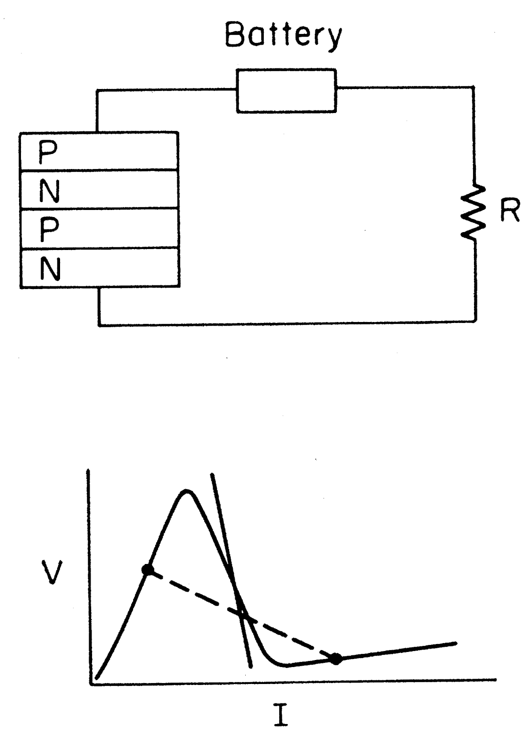


Fig. 11 (left). Darlington connection of transistors in a function block. Fig. 12 (right). A four-layer diode oscillator.

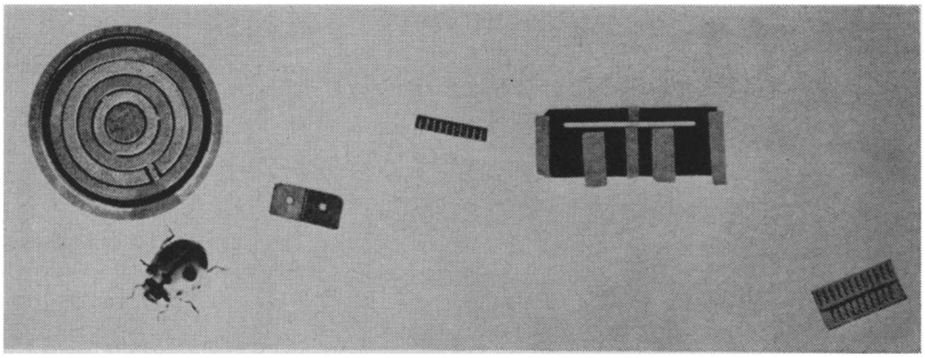


Fig. 13. A photograph of some Westinghouse functional electronic blocks.

handling present materials are required.

Two recent advances in materials modification are discussed here as showing the way to major future advances in function block development. One is the growth of germanium and silicon crystals in dendrite form (*13*). In semiconductor manufacturing practice it is necessary to cut thin wafers from large silicon boules. The process is wasteful of material because the saw is usually of nearly the same thickness as the slice. In addition, the surface layers of the wafer must be removed by etching to eliminate defects introduced by the cutting. Dendrites can be grown from the melt with optically flat surfaces. Proper control will result in ribbons of the width and thickness required for device fabrication. Since the surface of the dendrite as it is pulled is clean and undamaged, further processing can begin without intermediate surface preparations.

The second advance is the growth of epitaxial layers of silicon on a silicon substrate (*14*). By this means, the multiple junction layers required by the function block design may be provided. Earlier in this article functional blocks were described as having two, three, and four layers of various conductivity types. These layers are provided by crystal-growing and impurity-diffusion techniques. Unfortunately, these techniques do not provide the versatility needed to form an arbitrary number of layers with arbitrary electrical conductivities. Epitaxial growth provides this needed versatility and will make possible the construction of functional blocks which cannot be made by the older techniques.

Conclusion

The developments in microcircuitry discussed in this article are the beginnings of profound changes due to take place in electronics. The trend will be away from individual component circuits and toward the integration of circuit functions into functional blocks. The ever-increasing need for reliability will force the development of more reliable assemblies. Functional electronic blocks and two-dimensional techniques in combination will fill this need.

Size and weight are becoming more important in a wider and wider range of applications. Again, integration of components into functional blocks must be carried out to achieve the necessary reduction.

The boundaries between materials and devices and between devices and circuits are being removed, and we shall see an integration of disciplines in the future development of molecular electronics (*15*).

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15. In this rapidly developing field there is no standardized terminology. For example, the subject of this article has been called "solid circuits," "semiconductor networks," and "integrated circuits," as well as molecular electronics.